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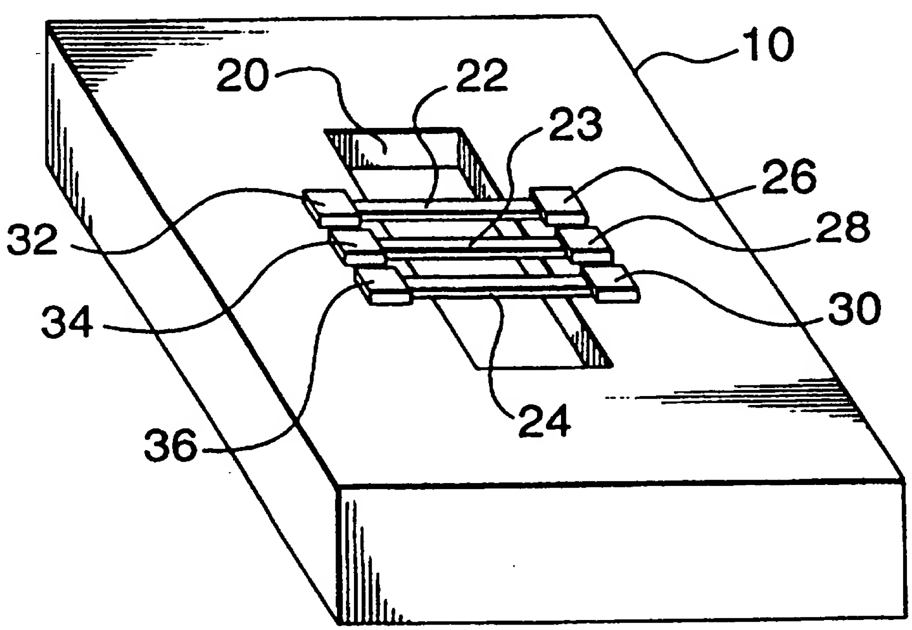
(54) Title: ACCELEROMETER WITHOUT PROOF MASS

(57) Abstract

An accelerometer having a substrate with a cavity therein, a heater wire extending over the cavity, a pair of temperature sensor wires extending over said cavity equidistant from said heater, and means for passing electrical current through the heater so as to develop a symmetrical temperature gradient in the fluid extending outwardly from the heater to the two temperature sensors. The fluid may be a liquid or a gas surrounding the heater and temperature sensors. Applied acceleration disturbs this symmetry and produces a differential temperature between the two temperature sensors proportional to the acceleration.



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ACCELEROMETER WITHOUT PROOF MASS

FIELD

The present invention relates to an accelerometer of a type having no proof or inertial mass and no moving parts or parts under stress such as piezo or strain gauge accelerometers.

BACKGROUND

Accelerometers find use in widely diverse applications including automobile air bags and suspension systems, computer hard disc drivers, smart detonation systems for bombs and missiles and machine vibration monitors. Silicon micromachined acceleration sensors are beginning to replace mechanical acceleration switches. Present accelerometers are all based upon the classical Newtonian relationship of force, F, mass, m, and acceleration, a, in which F = ma. Thus, for a cantilevered beam, the force due to acceleration causes the beam to deflect. This deflection is sensed either by sensing the change in piezo resistors or by a change in capacitance. Such systems are not stable over wide temperature ranges and have a response which peaks due to insufficient mechanical damping.

One form of accelerometer made by bulk micromachining consists of a membrane or diaphragm of silicon formed by chemical etching having a large mass of silicon at the centre and tethers of thin film piezo-resistors, whose resistance is sensitive to strain and deformation, suspending the mass. Acceleration causes the large silicon mass to move, deforming the diaphragm and changing the resistance of the piezo-resistors. Such bulk micromachined devices are large by integrated circuit standards and consistent with semiconductor circuit fabrication techniques.

Another system made by surface micromachining is based on a differential capacitor. Surface micromachining creates much smaller, more intricate and precisely patterned structures than those made by bulk micromachining. It involves the same process that is used to make integrated circuits, namely, depositing and etching multiple thin films and layers of silicon and silicon-oxide to form complex mechanical structures. In this case a central beam is affixed in an "H" configuration with the spaced apart parallel arms of the "H" supporting respective ends of the cross beam.

A plate affixed perpendicular to the beam forms a moving capacitor plate that is positioned between two fixed plates, thus, forming two capacitors sharing a common moving plate. When the unit is subjected to an accelerating force the beam and hence moving plate moves closer to one of the fixed plates and away from the other fixed plate. The effect is to reduce one of the capacitors and increase the other by an amount proportional to the acceleration. The device requires proper orientation with the cross beam parallel to the direction of acceleration. However, surface micromachining is used to create a much smaller device adapted to the same techniques used to make integrated circuits. The moving capacitor plate accelerometer suffers from high noise and exhibits drift at low acceleration measurements.

It is an object of the present invention to provide an improved accelerometer. It is a further object of the invention to provide an accelerometer having no proof mass and a corresponding increased ruggedness.

SUMMARY OF THE INVENTION

According to the invention there is provided an accelerometer having a substrate with a cavity therein, a

heater wire and a pair of sensor wires extending across the cavity with the heater wires equidistant from the heater and on either side thereof.

Preferably the substrate is silicon and the cavity, heater wire and sensor wires are made by micromachining. Micromachining is the technology without which practical accelerometers of the kind described herein cannot be produced.

The means for passing electrical current through the heater so as to develop a symmetrical temperature gradient extending outwardly from the heater to the two temperature sensors.

The heater wire and sensors may be polysilicon. Alternatively they may be a thin film of metal. A suitable metal may be selected from the group consisting of nickel, chromium, gold or platinum.

Advantageously, there may be provided means for measuring the differential resistance of the temperature sensors.

Means may also be provided to convert the differential temperature measurement to an acceleration value.

An auxiliary heater wire may be formed on each side of the heater wire and symmetrically disposed with respect to the heater wire.

BRIEF DESCRIPTION WITH REFERENCE TO THE DRAWINGS

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as other features and advantages thereof, will be best understood by reference to

the detailed description which follows, read in conjunction with the accompanying drawings, wherein:

Fig. 1 is a perspective view of a preferred embodiment of the accelerometer;

Fig. 2 is a graph showing the normal temperature gradient and the temperature gradient shift due to acceleration;

Fig. 3 to 6 are sectional views showing the steps in fabricating the device of Fig. 1;

Fig. 7 is a plan view of the device;

Fig. 8 is a schematic diagram of the circuitry used with the accelerometer; and

Fig. 9 is a top or plan view of the device incorporating two auxiliary heaters for self-testing.

Fig. 10 is a top view of a thermal accelerometer effective to measure acceleration along two perpendicular directions.

DETAILED DESCRIPTION WITH REFERENCE TO THE DRAWINGS

Referring to Figure **1** the accelerometer is formed on a silicon substrate **10** in which a cavity **20** is formed underneath a central heater **23** and sensors **22** and **24** positioned at equal distances from the heater **23** on either side thereof. Wire bonding pads **28** and **34** are formed on either end of the heater **23** to provide electrical contact thereto. Wire bonding pads **26** and **32** are formed on either end of sensor **22** and wire bonding pads **30** and **36** are formed on either end of sensor **24** also to provide electrical contact. Electrical current is passed through the heater 23 which heats the air around it. The

temperature gradient established is shown by the solid lines **34** and **36** in Figure **2**. Resistive temperature sensors **22** and **24** are used to measure the temperature of the surrounding air. The distance between the heater **23** and each sensor is about 100 microns while heater **23** is 10 to 15 microns wide. The length of the heater **23** and sensors **22** and **24** is approximately 500 microns. However, other dimensions may be selected depending upon the desired specifications of operation.

With the sensors **22** and **24** equidistant from the heater **23** the differential temperature between the sensors **22** and **24** will be zero. If the substrate **10** is subjected to an accelerating force in a direction perpendicular to the heater **23** but along the surface of the substrate, the temperatures distribution of the air will shift as shown in the dotted lines **36 and 38**. In this case sensor **22** will experience an increase in temperature whereas sensor **24** will detect a reduced temperature, giving a net non-zero differential temperature measurement between the sensors **22** and **24** of a magnitude which is proportional to acceleration. For the device to operate properly, it is placed in a sealed chamber so that the temperature gradient will not be disturbed by external air current or flow.

Referring to Figure **3**, the silicon wafer **12** is n-type. Thermal oxidation at 1,100 °C produces a layer of silicon dioxide **14** 0.5 µm thick. On top of the layer of silicon dioxide **14** a layer of polysilicon **16** 0.8 µm is deposited. The polysilicon layer **16** is lightly doped to increase its electrical conductivity. Following this doping, another oxidation step is used to develop a 0.5 µm thick layer of silicon dioxide **18** on top of the polysilicon **16** reducing the thickness of the polysilicon layer to 0.5 µm. Standard photolithographic techniques are used to pattern the silicon dioxide layer **18** over the polysilicon **16** as seen in Figure **4**. The silicon dioxide **18** is used as

an etch mask for the removal of exposed polysilicon using ethylenediamine-pyrocatechol-water (EDP) mixture as an etchant at 85 °C. Oxide **14** underneath the polysilicon **16** protects the silicon substrate **10** during etching. The resulting structure after etching shown in Figure **4** defines three polysilicon bridges that are used as the heater **23** and the two sensors **22** and **24**.

Another oxidation step produces oxide on the side walls of the polysilicon **16** to protect it from a later silicon etch. The oxide layers above and below the polysilicon layer **16** are patterned to create openings for the bonding pads and formation of the cavity in the silicon substrate as shown in Figure **5**.

An aluminum nickel seed layer is sputtered onto the wafer and photoresist is patterned so the exposed bonding pad area can be selectively plated with gold. The photoresist and seed layer are removed and the wafer is etched in EDP to create a deep cavity **20** underneath. During EDP etching of the silicon substrate **10**, the polysilicon bridges **22, 23**, and **24** are protected by the oxide layers and the polysilicon **16** underneath the bonding pads **26**, **28**, **30**, **32**, **34**, and **36** is protected by gold plated pads **44**.

The fabrication process is compatible with CMOS and bipolar processes. This allows the accelerometer to be integrated with signal conditioning circuits.

Referring to Figure **7**, the final device consists of three elongated strips each of which consists of a layer of polysilicon sandwiched between layers of oxide **22**, **23**, **24** coupled to their respective bonding pads and suspended over a cavity **20**. The space around the heater **23** and temperature sensors **22** and **24** is filled with either a fluid or a gas. Although polysilicon has been described

as the material of which the heater **23** and sensors **22** and **24** are made, thin film metal resistors such as nickel, chromium, gold or platinum can be used.

Heater **23** is used in a bridge circuit formed by resistors R1, R2, R_L, and R_R shown in Figure **8**. The junctions of the bridge are sampled by lines **46** and **48** and fed into the input of a differential amplifier **50** which provides an output on line **52**. When acceleration is applied, the balance of the bridge is disturbed causing a differential voltage to be applied to the amplifier **50**. The amplifier **50** converts the differential signal to a single-ended voltage at its output on line **52**. With R1 = R2, and no acceleration, $V_a=0$. When acceleration is applied this balance is disturbed and the differential voltage V_a is amplified and converted into a single-ended signal by the differential amplifier **50**.

Although micromachining was described as the technology used to produce this accelerometer, there are other low cost manufacturing technologies that can also be used. In order to maximize the differential temperature change of the sensors **22** and **24** the direction of acceleration is perpendicular to the heater **23** and along the surface of the substrate **10**, Acceleration perpendicular to the surface of the substrate will cause a change in the temperature gradient but will affect each sensor in the same way.

Referring to Figure 9, a self-testing capability can be implemented by the addition of two auxiliary heaters **23A** and **23B**, one on each side of main heater **23**. In normal operation, all three heaters **23**, **23A**, and **23B** are powered to produce a symmetrical temperature gradient which is disturbed only by acceleration. By switching off one of the auxiliary heaters **23A** or **23B**, this symmetrical temperature gradient is disturbed. For example, when

auxiliary heater **23A** is switched off, the point of symmetry of the temperature gradient will shift from the center of heater **23** towards sensor **24** without application of an acceleration. This change will produce an output to indicate that the accelerometer's function is intact. Switching off heater **23B** has a similar effect but in the opposite direction. Instead of cutting off the current completely, a more elaborate testing can be done by controlling the amount of auxiliary heater current reduction to anywhere between 0 and 100%.

Obviously, two or three accelerometers oriented at right angles to each other could be used to sense acceleration in two dimensions or three dimensions, respectively, rather than having to orient the accelerometer in the direction of the acceleration. By using a small heater plate in place of the long heater wire, and increasing the number of temperature sensors from two to four, as illustrated in Figure 10, this same device can be used to measure acceleration in two axes simultaneously.

A thermal accelerometer capable of detecting acceleration in 2 axes can be produced using the same principle as above. Illustrated in Figure 10 is the top view of a 2-axes thermal accelerometer **61**. It consists of a suspended structure **63** over an etched cavity **65**. At the center of this suspended structure is a small heater plate **60** which generates a symmetrical temperature gradient in both the X and the Y axes. Four temperature sensors, **62**, **64**, **66** and **68** are placed at equal distance from the heater plate. When acceleration is applied to the device in the X direction, differential temperature is registrated only by **62** and **66**, producing an output. Similarly when acceleration is applied to the device in the Y direction, differential temperature is registrated only by **68** and **64**.

Accordingly, while this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Various modifications of the illustrative embodiments, as well as other embodiments of the invention, will be apparent to persons skilled in the art upon reference to this description. It is therefore contemplated that the appended claims will cover any such modifications or embodiments as fall within the true scope of the invention.

I CLAIM:

1. An accelerometer, comprising:

a substrate having a cavity therein;

a heater wire extending across said cavity;

a pair of temperature sensor wires extending across said cavity, substantially parallel to and equidistant from said heater wire on either side thereof; and

a non-solid heat transfer medium surrounding said heater wire and said temperature sensor wires.

2. An accelerometer according to claim 1, wherein said substrate is silicon and said cavity, heater wire and sensor wires are made by micromachining.

3. An accelerometer according to claim 1, wherein said heat transfer medium is gas selected from the group consisting of a fluid and a gas.

4. An accelerometer according to claim 1, including means for passing electrical current through said heater so as to develop a symmetrical temperature gradient extending outwardly from said heater.

5. An accelerometer according to claim 1, wherein said heater wire and said sensors are thin film materials.

6. An accelerometer according to claim 1, including means for measuring the differential resistance of said sensors.

7. An accelerometer according to claim 1, wherein said heater and sensor wires are coated with silicon dioxide.

8. An accelerometer according to claim 1, including a pair of auxiliary wires symmetrically disposed about said heater wire.

9. An accelerometer, comprising:

a substrate having a cavity therein;

a heater wire extending across said cavity;

a pair of sensor wires extending across said cavity, substantially parallel to and equidistant from said heater wire on either side thereof;

a non-solid heat transfer medium surrounding said heater and temperature sensor wires;

means for passing through current through said heater wire so as to develop a symmetrical temperature gradient in the air surrounding said heater wire in which the air temperature lowers in a direction away from said heater wire; and

means for measuring the differential resistance of said sensor wires and relating that to acceleration in a direction transverse to said sensor wires and along the surface of said substrate.

10. An accelerometer according to claim 9, wherein said heater wire and said sensors are polysilicon.

11. An accelerometer according to claim 9, wherein said substrate is silicon.

12. An accelerometer according to claim 9, wherein said cavity, heater wire and sensor wires are made by micromachining.

13. An accelerometer according to claim 9, including an auxiliary heater wire symmetrically positioned on each side of said heater wire and proximate thereto.

14. A process for fabricating an accelerometer, comprising:

(a) heating an n-type silicon substrate at 1,100°C to form a layer of silicon dioxide;

(b) depositing a layer of electrically conductive material over said silicon dioxide;

(c) forming a silicon dioxide layer over said electrically conductive layer;

(d) patterning the silicon dioxide layer over the electrically conductive layer to form three spaced apart bridges of exposed electrically conductive material;

(e) etching the electrically conductive material using the silicon dioxide as a mask down to the silicon dioxide covering said substrate;

(f) heating the substrate so as to oxidize the side walls of the electrically conductive material in said bridges;

(g) patterning and etching the oxide layers above and below said bridges to create openings for bonding pads and to expose substrate for formation of a cavity below said bridges; and

(h) patterning and etching a deep cavity below said bridges.

15. A process according to claim 13, wherein said electrically conductive material is doped polysilicon.

16. A process according to claim 13, wherein said electrically conductive material is selected from the group consisting of nickel, chromium and platinum.

17. A process according to claim 13, including forming an auxiliary bridge symmetrically disposed on each side of a center one of said three bridges.

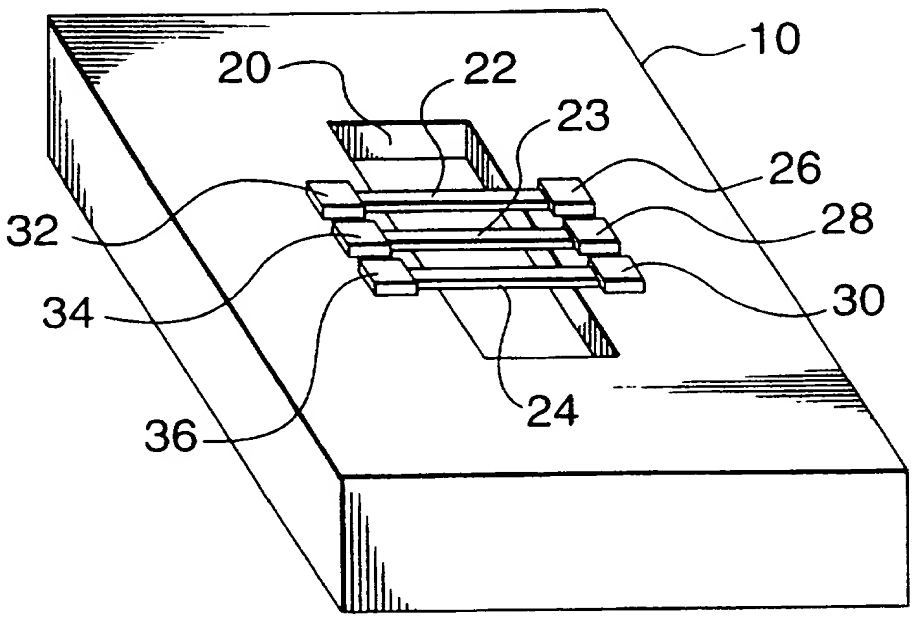

FIG. 1

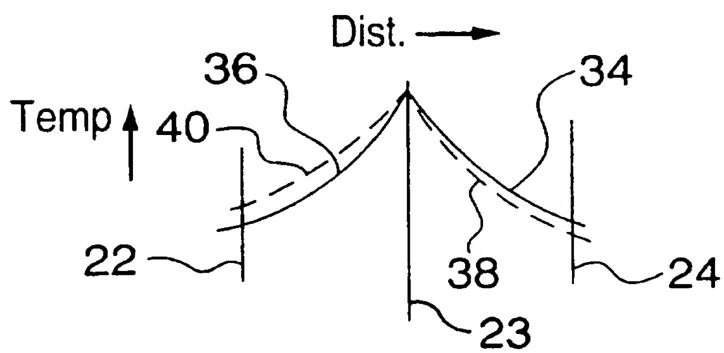

FIG. 2

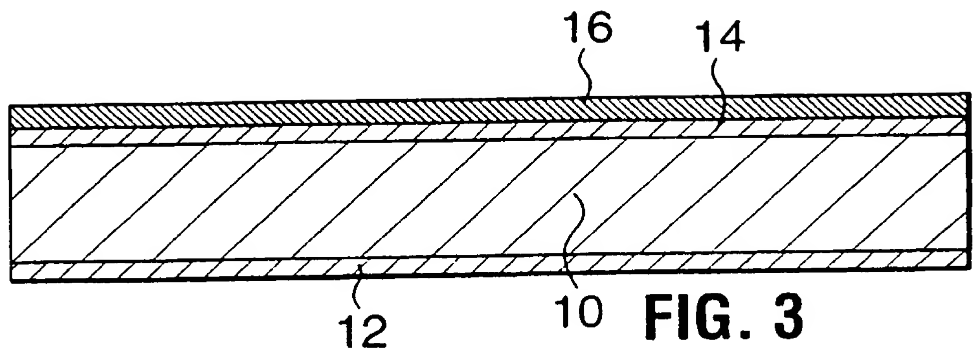

FIG. 3

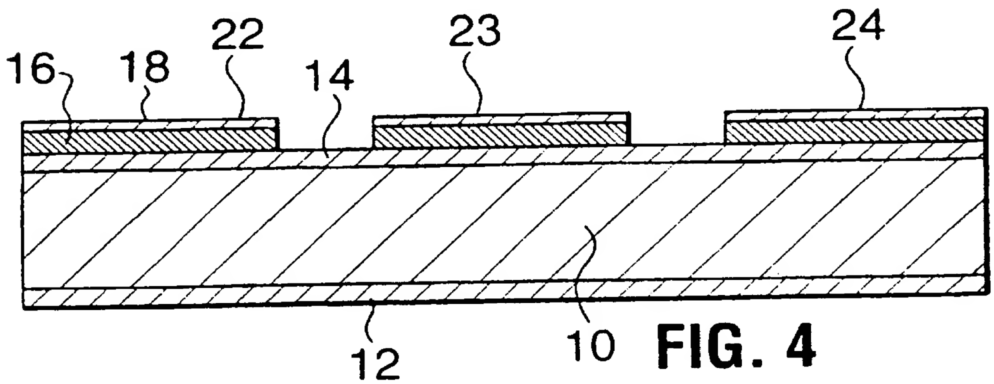

FIG. 4

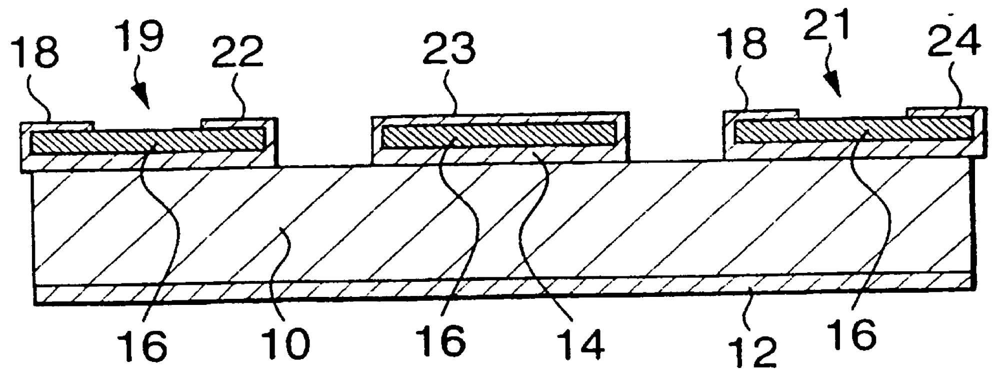

FIG. 5

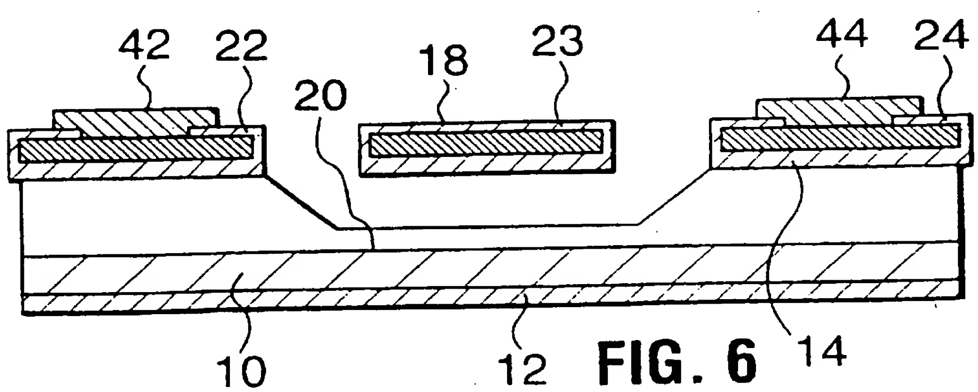

FIG. 6

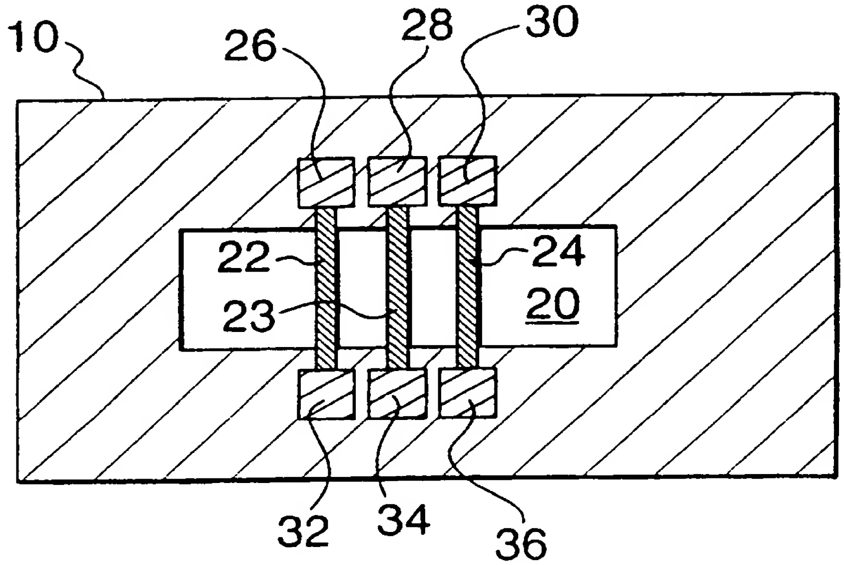

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FIG. 7

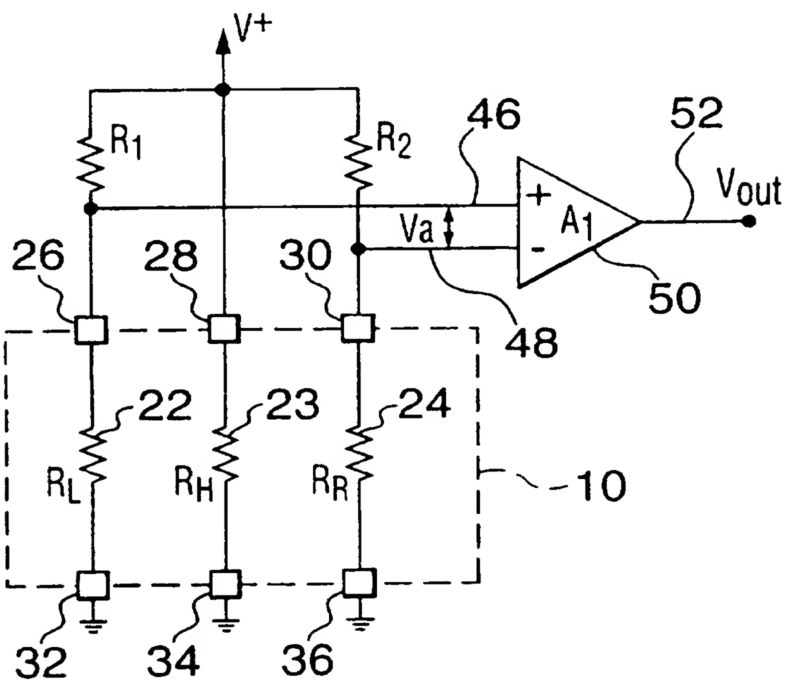

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FIG. 8

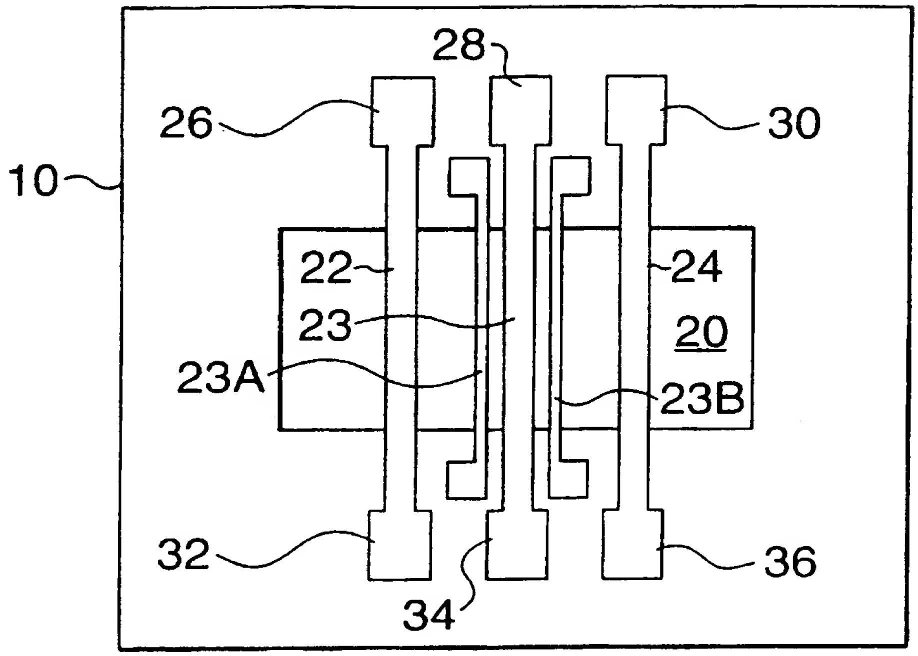

FIG. 9

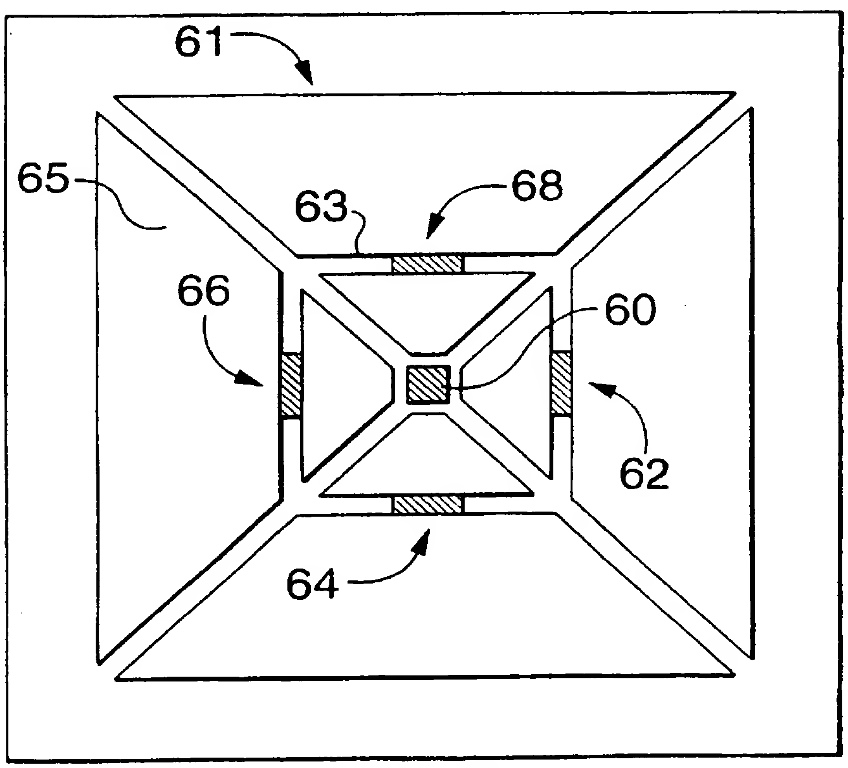

FIG. 10

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 97/00442

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01P15/00 G01P21/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 664 456 A (HONDA MOTOR CO LTD) 26 July 1995 see column 5, line 26 - line 42 see column 5, line 52 - column 8, line 8 see column 17, line 29 - column 18, line 42; figures 3-5,12,17,18 ---	1-9, 11-14, 16,17
X	EP 0 674 182 A (HONDA MOTOR CO LTD) 27 September 1995 see page 6, line 55 - page 7, line 20 see page 8, line 29 - line 35; figures 6,4B -----	1-6,9, 11,12

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☒ Patent family members are listed in annex.

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1

Date of the actual completion of the international search	Date of mailing of the international search report
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Information on patent family members

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0664456 A	26-07-95	JP 7209323 A	11-08-95
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